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A Cancellation Technique for Reducing Background Noise Within Turbulent Flow Environments Characterized by Pipes and Annuli

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Experimental studies of turbulent boundary layer wall pressure fluctuations are typically complicated by flow generated acoustic pressure levels which are superimposed on the turbulent fluctuations of interest. This problem can be particularly acute when the test fluid is water or similar liquid with a high bulk wave propagation velocity. The present paper describes a method for addressing this problem which permits wall pressure fluctuation experiments of high quality to be conducted within internal flow geometries over a bandwidth of 1 kHz. The method improves on a technique of ~~utilizing~~ 3 flush mounted transducers located within a coaxial plane, thereby providing up to 20 dB reduction over previous measurements for the bandwidth investigated. Experimental results show that ~~the utilization of~~ Using the improved technique allows measurements of both the nearfield and farfield pressure components. Excellent agreement with previously reported wall pressure fluctuation measurements is demonstrated for the geometries evaluated.

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A CANCELLATION TECHNIQUE FOR REDUCING BACKGROUND NOISE WITHIN TURBULENT FLOW ENVIRONMENTS CHARACTERIZED BY PIPES AND ANNULI

INTRODUCTION

Wall pressure fluctuations generated within turbulent fluid flows are of practical as well as fundamental significance. Besides adding to our interpretation and understanding of the physical phenomena present, these fluctuations can couple with various structures containing the flow, driving them in such a way as to cause structual failure. Depending on the design of the experimental facility and the properties of the flowing fluid, the background sound level can range from small to very large amplitudes when compared to the turbulent pressure fluctuations of interest. Hence, discriminating in some way between the two levels, better enables the researcher to reduce the contaminating background noise and accurately measure the pressure fluctuations of interest.

There have been a number of approaches in the past in investigating ways of reducing the effects of facility-generated noise from interferring with turbulent flow experiments. The simplest method is to design the facility with sound isolators, absorbers and linings such that extraneous noise is minimized as much as possible. A number of investigators (1-7) have reported on experiments utilizing such techniques. This has resulted in a fair degree of success in reducing the environmental noise within tolerable limits, usually on the order of the turbulent fluctuations being measured.

Another technique was introduced by Willmarth (8), who recognized that the typical experimental facility contains local source mechanisms of acoustic sound such as vanes, diffusers, bends in piping and pumps. Willmarth showed that a finite correlation was obtained for negative time delay between flush-mounted transducers separated in the streamwise direction. By combining this temporal quantity with the spatial separation between the two sensors, a velocity was derived equal to the sound speed (relative to the flow velocity) in the fluid. Willmarth interpreted this quantity as flow-generated acoustic noise and subtracted it from the original output to eliminate its contribution to the overall signal. However, application of this method has the disadvantages of being both tedious as well as introducing an additional source of error by massaging (correcting?) all data prior to any statistical analysis.

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A third technique employs a signal processing scheme introduced by Wambsganss et al. (9). and later refined by Wilson et al. (10). Utilizing three pressure transducers located in a plane perpendicular to the flow direction, this method employs simple subtraction in order to separate the signals due to the turbulent boundary layer pressure fluctuations, background acoustic and electronic noise respectively. Both Wambsganss and Wilson utilized this method to study turbulent flows through annuli.

This paper reports some refinements to this signal processing technique which minimizes the error in the resulting estimates of the wall pressure fluctuations. Experimental results are presented for pipe and annular flow geometries showing the ease with which the method may be applied.

CONCEPTS

We assume first that the turbulent boundary layer wall pressure fluctuations are stationary ergodic processes (11). We further assume that the instantaneous signal from each flush-mounted pressure transducer, F(x,t), can be represented as the linear superposition of three components:

$$F_i\,(x,t) \;=\; T_i(x,t) \;+\; A_i(x,t) \;+\; E_i(t). \tag{1}$$

Here, T, A and E represent the contribution to the total signal due to the turbulent boundary layer induced pressure fluctuations, the facility generated background noise and electronic noise respectively. As indicated, the acoustic and turbulence signals are functions of both space and time, whereas the electronic signal would be specific to the transducer itself and result in time dependence only. Using standard definitions for the correlation between any two time dependent signals over a finite time P, we have the following relation:

$$R(\tau)_{F_iF_j} \;=\; \lim_{P\to\infty}\frac{1}{P}\int_0^P F_i(t)F_j(t+\tau)dt. \tag{2}$$

The auto-correlation is defined for $i = j$ and the cross-correlation is for $i \neq j$. If the contaminating noise of an acoustic nature is generated several hydraulic diameters up or downstream of the test section, then the resultant pressure can be assumed to propagate in a plane wave (or axisymmetric mode for pipes). For low frequencies and stiff constraining supports, this propagating wave may be considered constant in magnitude and phase throughout any cross-sectional plane normal to the flow vector. This fact provides a means to conveniently eliminate this component from the instantaneous transducer output by subtracting signals from two transducers lying in this co-axial plane. Referring back to

Eq. (1), we see that the other major component is the turbulent term $T_i(x,t)$. In order not to eliminate any of this information from the resultant signal, the two transducers must be spatially separated far enough to assure zero correlation between the boundary layer wall pressure signatures. It is generally accepted that the coherence length between turbulent signals in a transverse direction from the flow would be somewhat less than the boundary layer thickness δ, hence determining a minimum length scale required. When the above conditions hold, we may make the following assumptions:

(1) $A_i(t)$ is uncorrelated with the turbulent fluctuations and the electronic noise.

i.e., (a) $\int_0^P T_i(t)A_j(t+\tau)dt = 0$, for all i,j

(b) $\int_0^P E_i(t)A_j(t+\tau)dt = 0$, for all i,j

(2) The turbulent fluctuations, $T_i(t)$, are uncorrelated with one another and with the electronic noise.

i.e., (a) $\int_0^P T_i(t)T_j(t+\tau)dt = 0$, for all i,j

(b) $\int_0^P T_i(t)E_j(t+\tau)dt = 0$, for all i,j

(3) The instrument noise in each transducer is uncorrelated with each other.

i.e., $\int_0^P E_i(t)E_j(t+\tau)dt = 0$, for all $i \neq j$.

When these assumptions are valid, the subtraction of two signal outputs eliminates the acoustic noise component directly,

$$F = F_A - F_B = T_A - T_B + E_A - E_B. \tag{3}$$

At this point, Wambsganss (who investigated the flow in an annulus), assumed that the electronic noise was negligible and the inner and outer wall pressure signals were equal. Auto-correlating the signal from Eq. (3) results in the following,

$$R(\tau)_{FF} = \lim_{p\to\infty} \frac{1}{P}\int_0^P \left[T_A(t) - T_B(t)\right]\left[T_A(t+\tau) - T_B(t+\tau)\right]dt \tag{4}$$

$$= \overline{T^2_{AA}(\tau)} + \overline{T^2_{BB}(\tau)} \tag{5}$$

$$= 2\overline{T^2_{AA}(\tau)}, \tag{6}$$

where the overbar refers to time/ensemble averages. From our understanding of turbulent flow within annuli and as represented in experimental results (10,12), Eq. (6) has been shown not to be valid. The outer wall rms pressure fluctuations exceed those on the inner wall with the difference increasing as the ratio of outer to inner radii increases.

Wilson refined this method by first auto-correlating Eq. (3) while maintaining the integrity of each respective component.

$$R(\tau)_{FF} = \overline{T_{AA}^2(\tau)} + \overline{T_{BB}^2(\tau)} + \overline{E_{AA}^2(\tau)} + \overline{E_{BB}^2(\tau)} \tag{7}$$

By combining Eq. (7) with two similar equations obtained through subtraction of the other two transducer pairs, a set of three equations with three unknowns may be obtained. By solving these equations simultaneously, the three turbulent terms. $\overline{T_{AA}^2}$, $\overline{T_{BB}^2}$, and $\overline{T_{CC}^2}$ could be obtained once the zero flow signals $\overline{E_{AA}^2}$, $\overline{E_{BB}^2}$ and $\overline{E_{CC}^2}$ were recorded. There is one major objection to the use of this method. There is a distinct disadvantage when the turbulent signal is of the same order of magnitude as the acoustic signal A(t). The resulting solution requires substractions between relatively large numbers to get a smaller one, contributing more uncertainty in the results. However, it represents a large improvement over the method of Wambsganss.

The authors propose an improvement to this subtraction technique which involves simply cross-correlating two different subtracted signals from three coplanar pressure sensors as illustrated below,

$$F_1 = F_A - F_B = T_A - T_B + E_A - E_B \tag{8}$$

$$F_2 = F_A - F_C = T_A - T_C + E_A - E_C \tag{9}$$

$$R(\tau)_{F_1F_2} = \lim_{P\to\infty} \frac{1}{P}\int_0^P F_1(t)F_2(t+\tau)dt. \tag{10}$$

Assuming the assumptions outlined previously remain valid, the following result is obtained,

$$R(\tau)_{F_1F_2} = R(\tau)_{AA} = \overline{T_{AA}^2(\tau)} + \overline{E_{AA}^2(\tau)}. \tag{11}$$

All that remains is to measure the auto-correlation of transducer "A" under zero flow conditions to obtain $\overline{E_{AA}^2}(\tau)$ and subtract it from Eq. (11) to obtain the turbulent pressure auto-correlation at location A. One may note, that if the electronic signal $E_A(t)$ is sufficiently lower (say 30-40 dB) than the fluctuating turbulent pressure signal, then Eq. (11) gives the desired results directly. Of course, similar subtracted signals may be derived for the other pressure correlations $R(\tau)_{BB}$ and $R(\tau)_{CC}$.

This method is immediately adaptable to either longitudinal or circumferential cross-correlations to ascertain eddy length scales and convection properties. Referring to Fig. 1, the following relations may be obtained for both indicated geometries as,

$$F_1 = F_B - F_A \tag{12}$$

$$R(\tau)_{F_1 F_D} = \lim_{P\to\infty} \frac{1}{P}\int_0^P F_1(t)F_D(t+\tau)dt \tag{13}$$

$$R(\tau)_{BD} = \overline{T^2_{BD}(\tau)}. \tag{14}$$

As indicated, the cross-correlation of two partially coherent turbulent signals in the flow may be obtained directly with no additional subtractions required. In order to obtain the spectral content of the turbulent signals, one only needs to Fourier transform the respective correlations.

EXPERIMENTAL APPARATUS AND RESULTS

The signal processing technique outlined above was employed to measure the turbulent boundary layer and facility generated noise induced wall pressure fluctuations in fully developed pipe and annular (external wall only) flow geometries. Figure 1 shows the coplanar arrangement of three transducers located in the external walls for the piping arrangements. For a rectangular channel, one would place the three transducers as represented by A, B and C in Fig. 1 in the external wall, side by side in a transverse direction to the flow. The flow facility is a blow-down water tunnel operated by the Laboratory of Computational Physics and Fluid Dynamics at the Naval Research Laboratory and is illustrated in Fig. 2. There are two test sections for the facility. The first is a piping arrangement (used in this study) and the second (not shown) is rectangular in cross-section with an aspect ratio of 18:1. The damped pipe test section, indicated in Fig. 2, consists of 1.83 m long, 19.1 cm inside diameter acrylic or polyvinyl-chloride (PVC) pipe sections supported every 1.83 m on solid cinder-block/concrete foundations. For the annular configuration, the inner cylinder was constructed of a 3.81 cm OD brass bar which was supported every 1.83 m by three 0.32 cm OD rods. To insure that a fully developed turbulent flow was present in both the pipe and annular test sections, the pressure sensors were placed within the outside walls more than 100 hydraulic diameters downstream from the ball valve (indicated in Fig. 2). More detailed information on the facility and its operating characteristics are provided elsewhere (13,14,15).

The flush-mounted sensors are capacitive/pre-amp combined units (0.23 cm in diameter) manufactured by Clevite Corporation of Bedford, Ohio and are similar to those used by Bakewell et al. (2). Each combined unit was matched in phase and exhibited a flat frequency response from DC to 10,000 Hz. Each experimental run was limited in duration from 1 to 3 minutes by the volume of the upstream liquid reservoir. Each sensor output was recorded on a 14 channel Hewlett Packard magnetic tape recorder to be analyzed later. Processing of the data was done on a dual channel 400 B omniferous FFT analyzer which could process two channels of data simultaneously in real time. Excellent resolution was obtained through 800-element alias-free frequency functions computed from dual 2048 point sampled time histories. For the present study, 100 ensemble averages of each function over a 1 KHz bandwidth was found to adequately represent the time independence of the stochastic processes being investigated.

The results for the pipe and annular configurations are presented in Figs. 3 and 4 respectively for a typical sensor. The non-dimensionalization used is consistent with other investigators, with ω denoting the radian frequency, δ_m one half the diameter ($(r_0 - r_i)/2$ for annular flow) and U_{avg} the average bulk velocity obtained through conservation of mass. PSD refers to the power spectral density (Pa^2/Hz) and ρ is the fluid density. As illustrated, the level of facility related sound (obtained by cross-correlating two coplanar sensors) is approximately 5-10 dB below the level of turbulent fluctuations over 1 KHz. This level increases somewhat in the annular configuration with slight fluctuations in the turbulent spectrum T, as might be expected when changing to the more restricted flow regime. Figure 5 shows that, for both pipe and annular flows, the pressure spectrum scales with outer variables for all velocities investigated.

Finally, a typical run of pipe flow data is compared in Fig. 6 to similar results in the literature with excellent agreement. It should be noted that Bakewell's (2) data has been corrected for high frequency cancellation according to the method proposed by Corcos (17), whereas the present data and that of Clinch (5) have not. The excellent comparison of our data to Bakewell's suggests that the transducers used in this study combined with the technique presented here have produced excellent resolution and accuracy and hence the Corcos correction was felt unnecessary.

CONCLUSIONS

High quality wall pressure fluctuation experiments have been conducted within two internal flow configurations with the following basic results.

(1) A new signal processing technique has been presented which utilizes the various subtracted signals from three coplanar sensors. The method was shown to represent a more straightforward approach than those previously reported .

(2) By cross-correlating two coplanar transducers which are spatially separated such that zero turbulent correlation is achieved, a measurement of the background facility generated noise levels may be recorded.

(3) The method has been shown to be easily applied to estimating finite correlations which may or maynot exist between two closely spaced transducers.

The effectiveness of this method is limited to acoustic noise which propagates in a plane wave. In order to determine the relative merits of applying this technique to higher order propagation, an error analysis would have to be conducted. Such an endeavor is planned in the near future.

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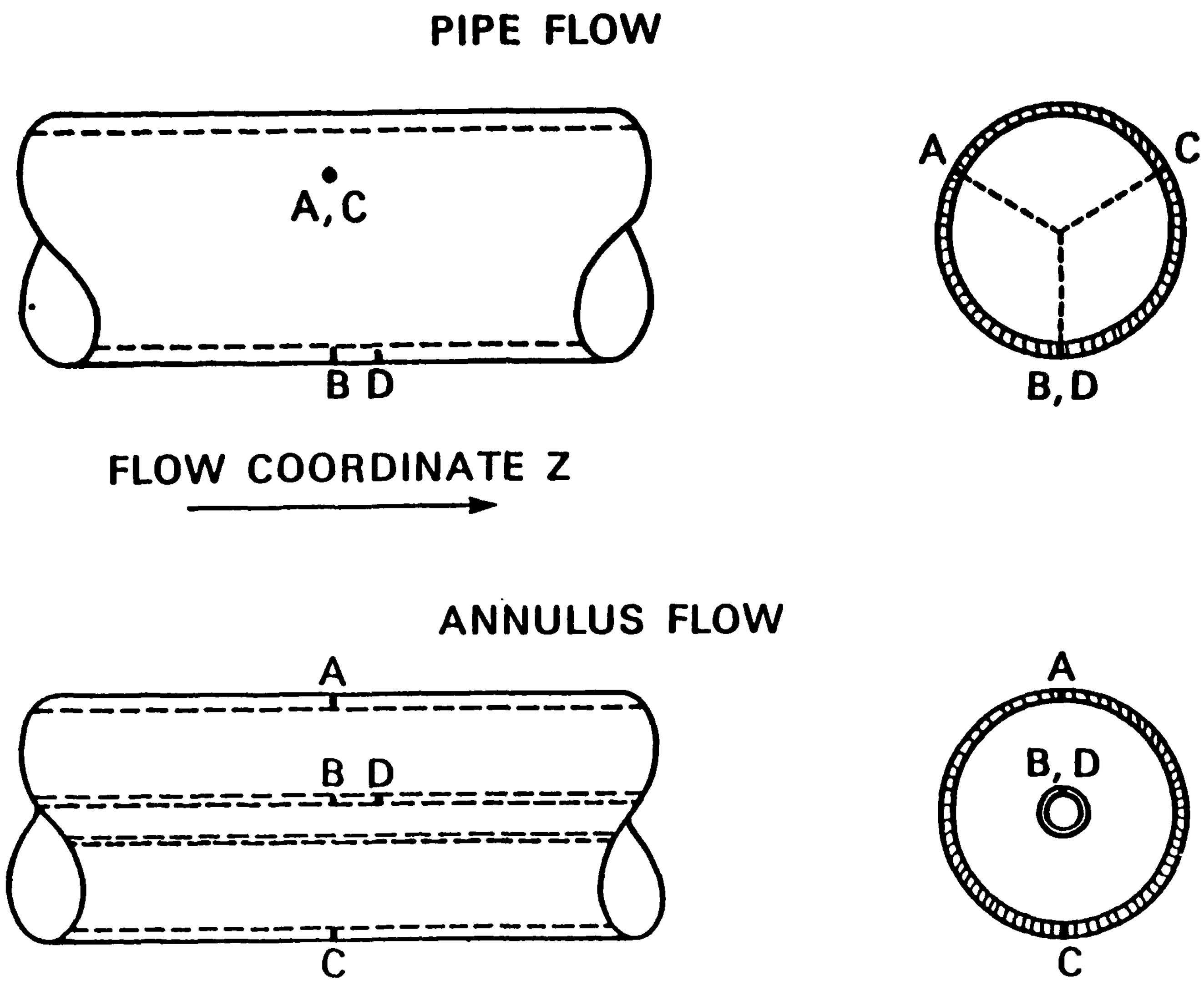

Figure 1. Planar emplacement of flush mounted pressure sensors within pipe and annular flow configurations.

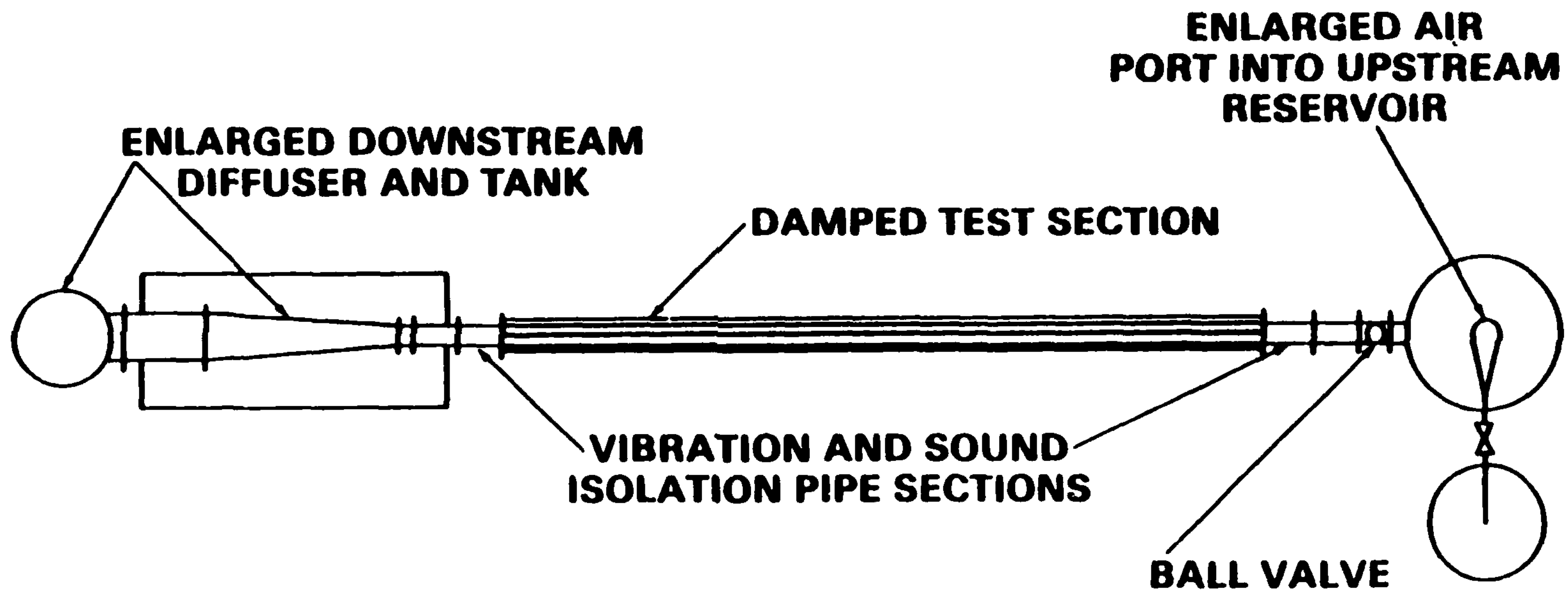

Figure 2. Blow down water tunnel in the Laboratory of Computational Physics and Fluid Dynamics at the Naval Research Laboratory.

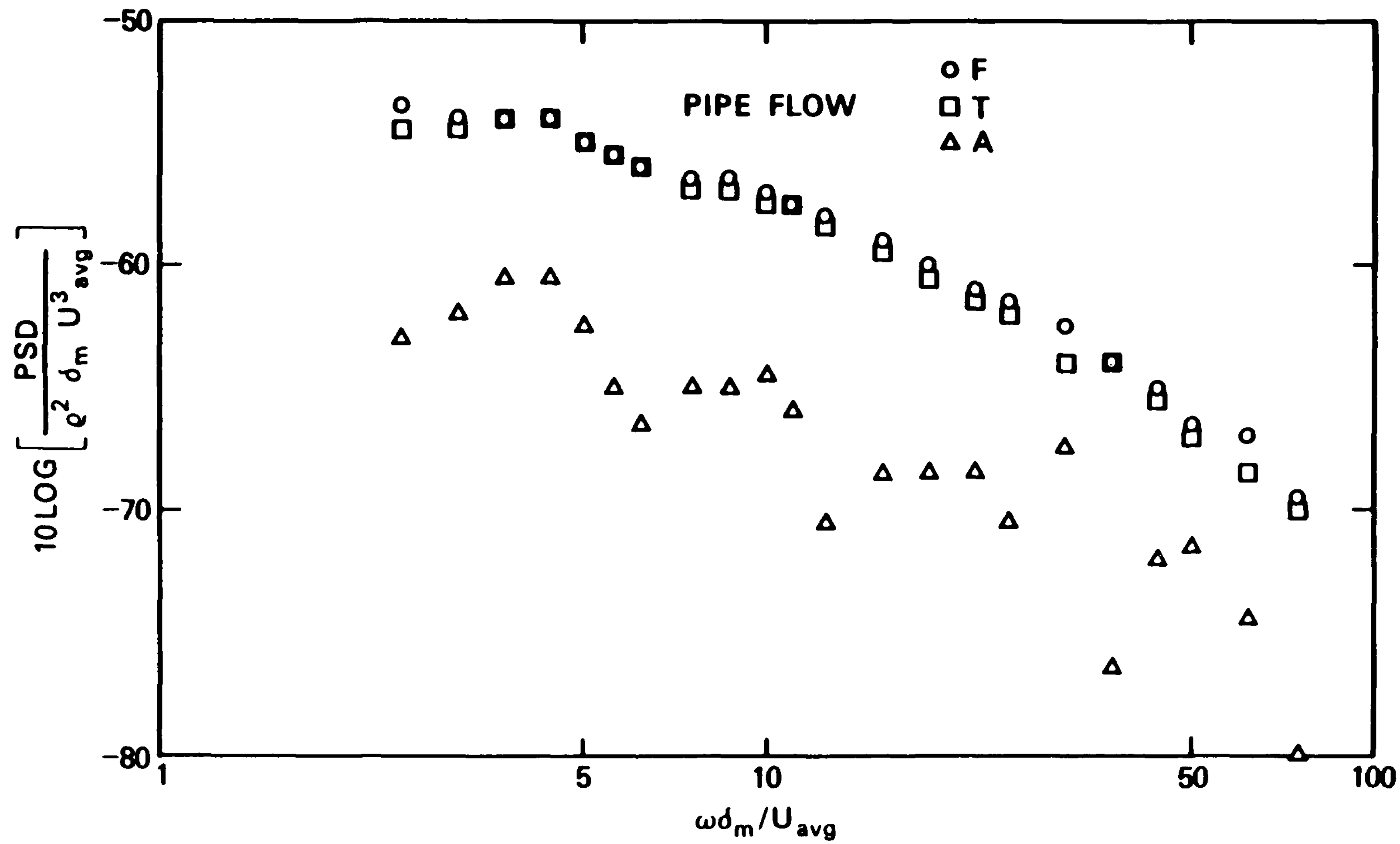

Figure 3. Pipe flow pressure spectra at U_{avg} equal to 11.3 m/sec.
(F=total pressure signal, T=turbulent boundary layer pressure fluctuations and A=propagating acoustic noise.)

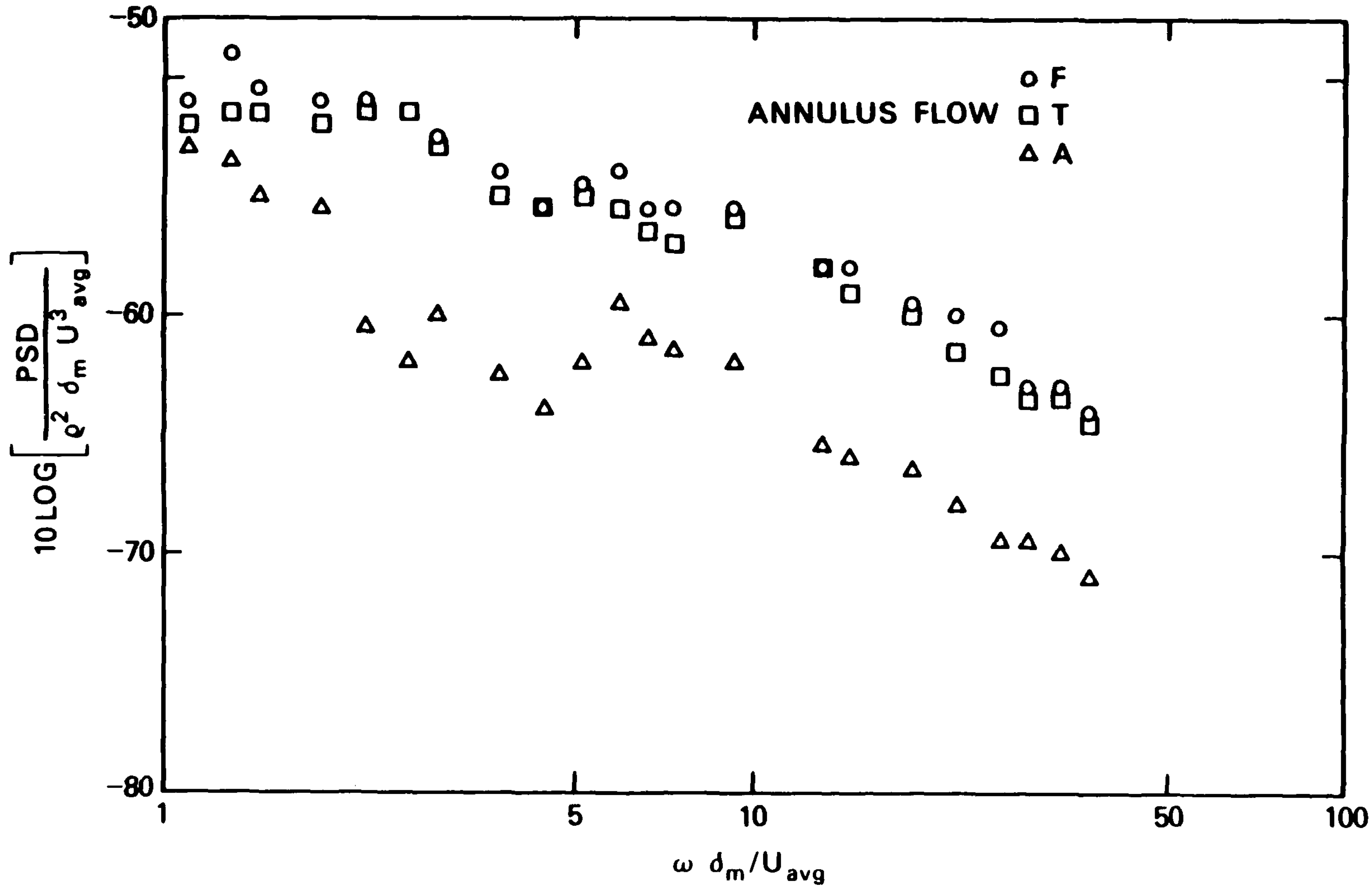

Figure 4. Annular pressure spectra at U_{avg} equal to 6.5 m/sec.

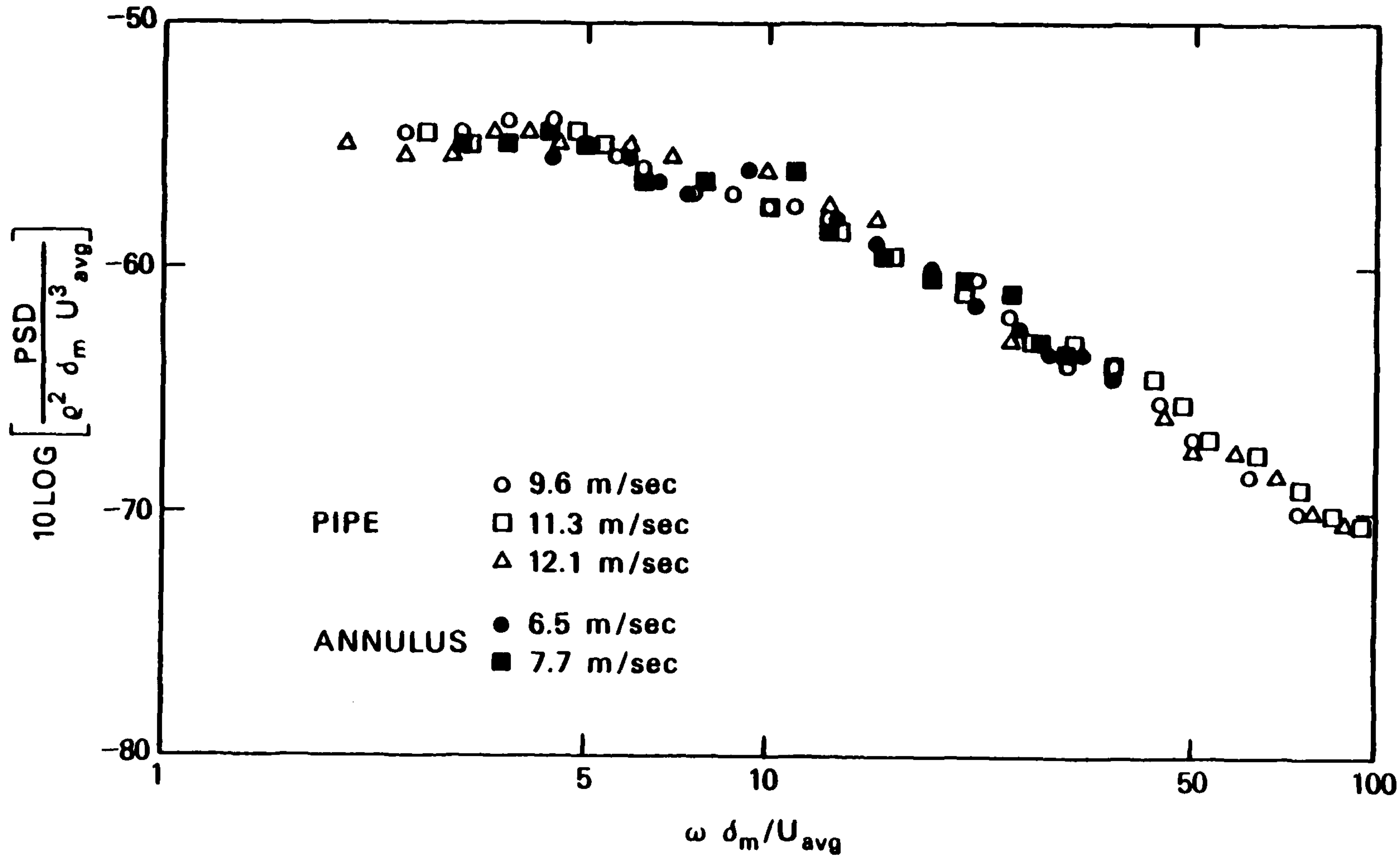

Figure 5. Pressure spectra comparison of the turbulent boundary layer fluctuations at typical flow velocities in both geometries.

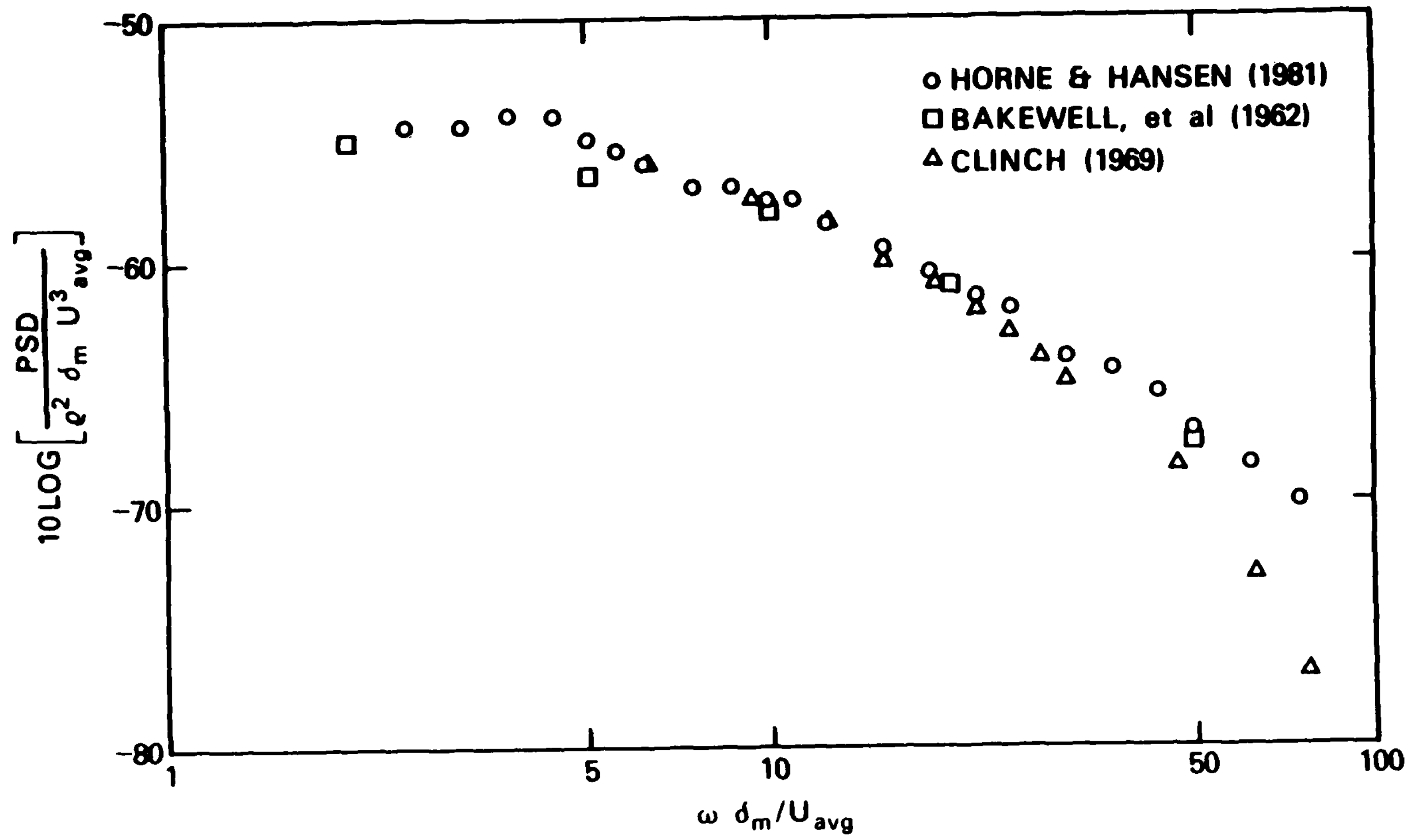

Figure 6. Turbulent pressure spectra comparison at a flow speed of approximately 11.0 m/sec for pipe flow. (see refs. 2 and 5 for Bakewell and Clinch respectively.)